

HYBRID SUPERCONDUCTING-MAGNETIC FAULT CURRENT LIMITER *

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Abstract

This limiter is intended to protect high-speed electronic circuits from subnanosecond duration high voltage transients. It operates at liquid nitrogen temperature and could be used in cryogenic electronic systems based on high- T_c superconducting devices. The device operates because of electric current induced switching from the superconducting state to the normal state and electric field induced resistance changes in manganite. The attenuation in high-speed transmission lines occurs, when, as the result of the action of a current pulse, the resistance of the superconducting $Y_1Ba_2Cu_3O_{7-x}$ strip, connected in series with the transmission line, increases, while the resistance of the manganite $La_{0.67}Ca_{0.33}MnO_3$ film, connected in parallel to this line, decreases. The attenuation achieved by such limiters exceeds 20-30 dB. In its non-attenuating regime, the bandwidth of the device could be up to 18 GHz.

I. INTRODUCTION

As modern electronics becomes smaller in size and more sophisticated, it becomes more susceptible to both front door and back door attack from both manmade and natural sources of electromagnetic energy. Considerable work has been done to develop technologies to protect against back door attack and to a limited extent against front door attack. However, only a very few researchers have attempted to develop a limiter for protecting the front door of electronic systems from very short (≤ 1 ns) pulses with very high amplitudes. In this paper, we shall introduce one possible limiter that could offer this protection.

It was demonstrated that electric current and field induced resistance change in high- T_c superconductors and magnetic materials can be used limit the amplitude of subnanosecond rise time electrical pulses [1-4]. A limiter based on superconducting materials contains thin film strips connected in series to a transmission line. When the current in this line exceeds a critical value (I_c), the strip,

which was initially cooled below the critical temperature (T_c) of the superconducting-normal state transition, is transformed to a resistive state. This induces additional attenuation of the signal propagating in the line. In the case of limiters based on magnetic materials exhibiting fast electro-resistance phenomenon [5], the limiters have to be connected in parallel to the transmission line and kept at temperatures close to the ferromagnetic-paramagnetic phase transition temperature (T_m) [3,4]. Both these devices have symmetrical current-voltage characteristics and can protect the input of high-speed electronic equipment against bipolar EMP. The superconducting limiter can be used to protect electronics from high-voltage fault current pulses (hundreds of volts), however, the threshold voltage at which this limiter starts to operate is several tens of volts. The limiter based on magnetic materials is a low threshold voltage device and it can not withstand high overvoltages.

In this paper, we propose a hybrid superconducting-

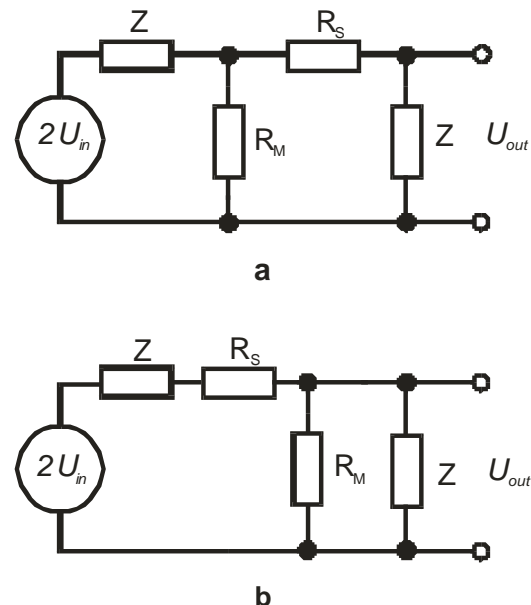


Figure 1. Two possible equivalent circuits for the HSM limiter.

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| 14. ABSTRACT This limiter is intended to protect high-speed electronic circuits from subnanosecond duration high voltage transients. It operates at liquid nitrogen temperature and could be used in cryogenic electronic systems based on high-Tc superconducting devices. The device operates because of electric current induced switching from the superconducting state to the normal state and electric field induced resistance changes in manganite. The attenuation in high-speed transmission lines occurs, when, as the result of the action of a current pulse, the resistance of the superconducting Y1Ba2Cu3O7-x strip, connected in series with the transmission line, increases, while the resistance of the manganite La0.67Ca0.33MnO3 film, connected in parallel to this line, decreases. The attenuation achieved by such limiters exceeds 20-30 dB. In its non-attenuating regime, the bandwidth of the device could be up to 18 GHz. | | | | | |
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magnetic (HSM) limiter made by combining both of these devices into one that exhibits low threshold voltages and that operates up to high voltages. Such a limiter could be used for protection of cryogenic electronic systems against short rise time electromagnetic pulses (EMPs).

II. LIMITER OPERATION

The analysis of HSM limiter operation can be made on the basis of a 50 Ω impedance electrical circuit, consisting of a superconducting strip and a diode with its interelectrode space filled with magnetic material. Two possible equivalent circuits for such a HSM are presented

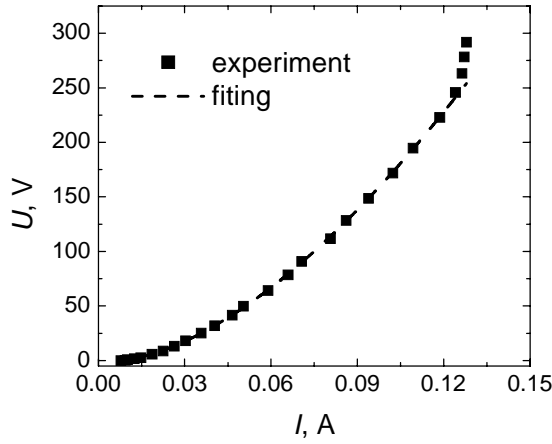


Figure 2. Voltage vs. current characteristic of $Y_1Ba_2Cu_3O_{7-x}$ strip ($l=3$ mm, $w=100$ μm , $d=0.1$ μm) measured using 0.4 ns rise time, 5 ns duration electrical pulses at a temperature of 80 K.

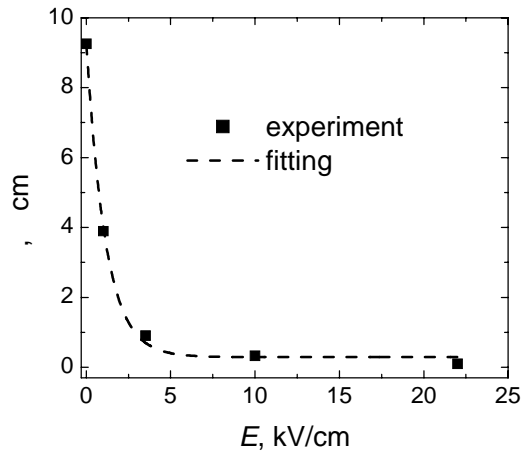


Figure 3. Specific resistance vs. electric field strength dependence of 50 nm thickness $La_{0.67}Ca_{0.33}MnO_3$ film at a temperature of 80 K.

in Fig.1 (a,b). In order to design a practical HSM, both the superconductor and magnetic devices have to be made from thin polycrystalline films. In this case, it is typical for the voltage–current characteristic of $Y_1Ba_2Cu_3O_{7-x}$ film to have a wide region of currents at which the film can be transformed to the resistive state (see Fig.2). The specific resistance of the superconducting film depends on the overcurrent as follows:

$$\rho = \frac{(w_s d_s)^{k_s}}{l} \alpha_1 \frac{(j - j_c)^{k_s}}{j} \quad (1)$$

where l , w_s and d_s are strip length, width, and thickness, respectively.

A polycrystalline structure is also essential for the manganite films in order to obtain the electro-resistance phenomenon. Figure 3 demonstrates typical specific resistance vs. electric field dependence at a temperature of 80 K for $La_{0.67}Ca_{0.33}MnO_3$ films prepared by laser ablation technique onto MgO substrate. This dependence is well approximated by following empirical formula:

$$\rho = \rho_0 + \rho_1 \exp\left(-\frac{E}{k_m}\right) \quad (2)$$

Using Eqs. (1), (2), (3), and (4), it is possible to obtain the U_{in} vs. U_{out} dependence of the HSM limiter's:

$$\frac{U_{in}}{U_{out}} = \frac{2R_m Z}{Z(R_s + Z) + R_m(R_s + 2Z)} \quad (3)$$

Figure 4 demonstrates how the attenuation (L) of a 50 Ω impedance transmission line containing a HSM limiter depends on the input voltage (U_{in}). The calculation of L

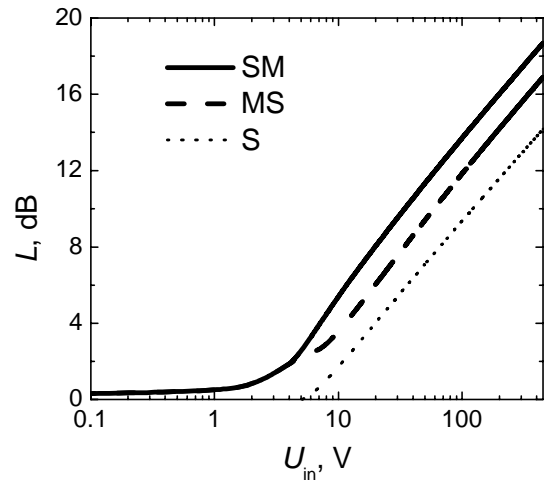


Figure 4. Attenuation (L) vs. input voltage (U_{in}) for superconducting limiter (dotted line), HSM limiter with magnetic switch connected before (dashed) and after (solid) superconducting strip.

vs. U_{in} dependence was performed using experimental data presented in Fig. 2 and Fig. 3. Based on the results of this calculation, the following main features of the HSM limiter were identified:

- 1) The threshold voltage (V_{th}), i.e. voltage at which attenuation exceeds 0.7 dB, of the HSM for both circuits presented in Fig.1 is the same and is determined by the parameters of the magnetic material.
- 2) The operation of the superconducting part of the HSM limiter starts at lower voltages if the magnetic switch is connected before the superconductor strip (circuit presented in Fig.1 a).
- 3) Total attenuation achieved using the HSM limiter is larger than in the case of single superconducting or magnetic limiters.
- 4) HSM limiters designed according to the circuit presented in Fig.1a exhibit higher maximal operation voltages because the superconducting strip protects the magnetic switch against high overvoltages.

III. LIMITER'S TECHNOLOGY

In order to make HSM limiters from $Y_1Ba_2Cu_3O_{7-x}$ superconductors and $La_{0.67}Ca_{0.33}MnO_3$ magnetic

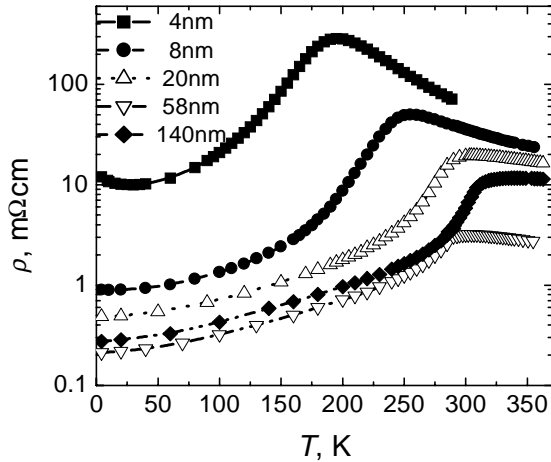


Figure 5. Specific resistance vs. temperature dependence for $La_{0.70}Sr_{0.3}MnO_3$ films with different thickness prepared on $NdGaO_3$ substrate

materials, it is necessary that the current and electric field induced resistance change in these materials be sufficiently strong. As mentioned earlier, only polycrystalline films are suitable for this purpose. Our investigations showed that such films could be prepared on substrates with lattice parameters different from the lattice parameters of the film. Moreover, in order to design high-speed limiters, it is necessary that the substrate dielectric constant be small. We found that MgO and lucalox (99.9% Al_2O_3 doped with MgO) substrates

satisfied these requirements. However, there is a large difference between the typical temperatures of phase transition for $La_{0.67}Ca_{0.33}MnO_3$ ($T_m=290K$) and $Y_1Ba_2Cu_3O_{7-x}$ ($T_c = 87K$) films. This makes it difficult to match the operation temperature for superconducting and magnetic switches. This matching can be achieved by decreasing the T_m of the manganite film by changing film thickness and by mismatching the lattice parameters of the substrate and the film. Figures 5 and 6 demonstrate these effects.

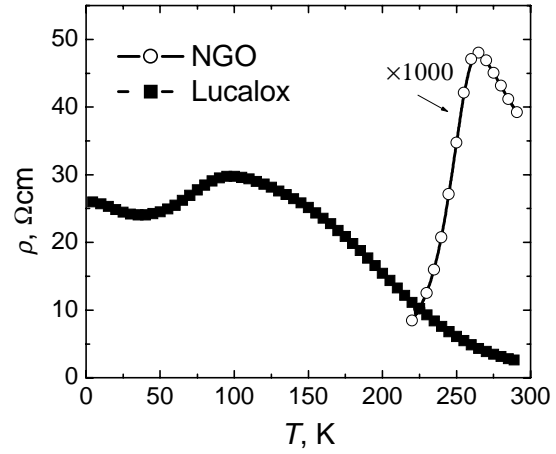


Figure 6. Specific resistance vs temperature dependence for $La_{0.67}Ca_{0.33}MnO_3$ films prepared on $NdGaO_3$ and lucalox substrates using laser deposition.

Also, it has to be noted that the growth of superconducting films on different substrates is more complicated in comparison to manganite film. For example, lucalox substrate can not be used for direct $Y_1Ba_2Cu_3O_{7-x}$ film deposition. In this case, a special intermediate layer has to be created between the substrate and the film. For this reason MgO substrate is more suitable, as both superconducting and magnetic films can be grown directly onto the surface of MgO without any additional technological efforts.

IV. CONCLUSIONS

It was demonstrated that the combination of fast superconductor and magnetic electrically guided switches enables one to design hybrid superconducting-magnetic limiters that can be used to protect the inputs of high-speed cryogenic electronic systems from short electromagnetic pulses. These devices are fabricated from polycrystalline films deposited on low dielectric constant substrate and operate at liquid nitrogen temperatures. It exhibits low threshold and high maximal operating voltage.

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